

# **Lunar Reconnaissance Orbiter Orbit Determination Accuracy Analysis**

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# Mission Profile

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- The Lunar Reconnaissance Orbiter (LRO) was designed to improve knowledge of the Moon's surface, topography, and radiation environment, to search for ice and to study permanently shadowed regions of the Moon.
- LRO launched on June 18, 2009 and entered lunar orbit on June 23, 2009.
- LRO flew in an elliptical (40 km x 180 km altitude) frozen commissioning orbit from June 27 until September 15, 2009.
- LRO was in its nominal mission orbit (50 km circular) from September 15, 2009 until December 11, 2011.
- LRO entered its extended mission orbit, the same 40x180 km altitude frozen orbit as the early commissioning orbit, on September 15, 2009 and has remained there since.

# Orbit Maintenance

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- During its nominal (low circular orbit) mission phase, LRO executed a station-keeping (SK) maneuver every 27 days and a momentum dump maneuver (DH) typically every 14 days
  - The frequency of DH events varies with Beta angle and spacecraft activity.
  - Momentum dumps were executed in conjunction with SK maneuvers when they occurred in the same week.
- In the current extended mission orbit SK maneuvers are only required yearly, and momentum dump maneuvers are still required every two to four weeks.

# FDF Support for LRO

- The Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF) performs daily operational orbit determination (OD) and related product generation for the LRO mission, in support of mission planning, network scheduling, and science operations.
- FDF OD accuracy requirements are
  - Definitive ephemeris accuracy of 500 meters total position root mean squared (RMS) and 18 meters radial RMS,
  - Predicted orbit accuracy less than 800 meters root sum squared (RSS) over an 84-hour prediction span.
- The LRO Lunar Orbiter Laser Altimeter (LOLA) science team also receives and processes LRO tracking data for the purpose of high-precision orbit reconstruction and gravity field estimation in support of the LRO laser altimeter.
  - The LOLA science team has previously published work describing their results performing high-precision OD for LRO using GEODYN. References can be found in the paper.

# LRO Tracking Data

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- LRO is tracked by a NASA station at White Sands and by Universal Space Network stations in Australia, Hawaii, Germany, and Sweden
  - 50% to 60% of the tracking is from the White Sands station.
  - DSN tracks only during station-keeping and most momentum unloads.
- Stations provide S-Band range and range-rate tracking.
- The S-Band tracking has a few issues
  - USN range-rate tracking exhibits an approximate -1 cm/sec measurement bias,
  - USN ranging exhibits an approximate -2 millisecond timing bias,
  - White Sands ranging exhibits an approximate +6 millisecond timing bias.

# FDF Modeling and Estimation of LRO

- The FDF uses the Goddard Trajectory Determination System (GTDS) for LRO Orbit Determination (OD)
  - GTDS is a batch least-squares estimator.
- Enhancements were made to GTDS to support LRO
  - Gravity modeling was increased to 360x360,
  - Solid lunar tide modeling,
  - Lunar albedo and lunar thermal radiation pressure,
  - Multi-plate spacecraft area model.
- Throughout the nominal mission and into the early extended mission the FDF modeling employed...
  - LP150Q gravity modeling at 150x150,
  - The DE421 ephemeris,
  - Applied  $C_R$  using a “cannonball” area model,
  - Solid lunar tides,
  - A 60-hour arc for orbit determination.
- FDF OD estimates the spacecraft position and velocity, and multiple (arc-segmented) range-rate biases, but not SRP.

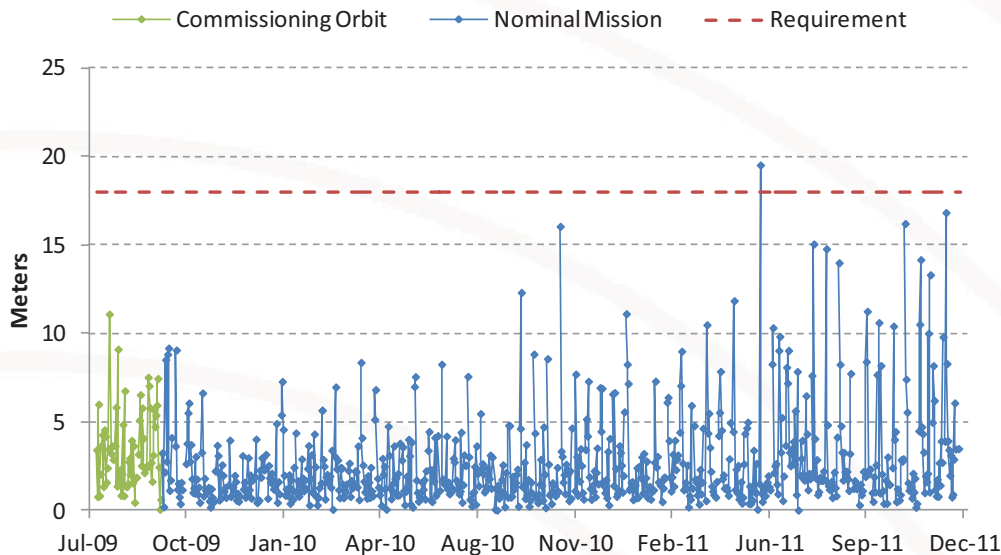


# Orbit Plane Geometry and Accuracy



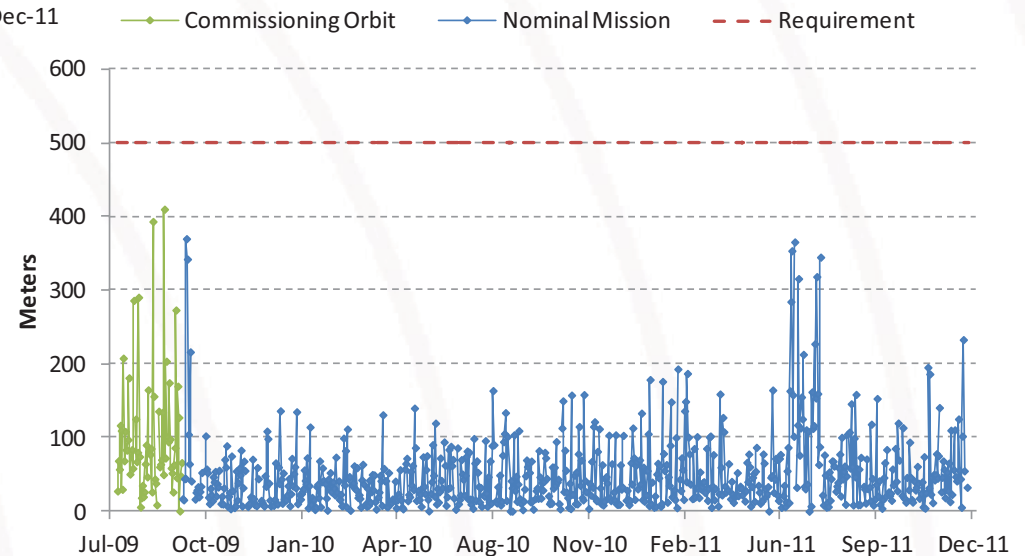
- LRO OD accuracy is impacted by two effects dependent on Earth-LRO orbit geometry
  - A degradation in radial accuracy occurs when the LRO orbit is viewed “face-on” from the Earth,
  - A degradation in cross-track accuracy occurs when the LRO orbit is viewed “edge-on” from the Earth.
  - Each of these effects has an approximate two-week period.
- Additionally, twice yearly, around Beta angles of  $\pm 90$  degrees, LRO is in full-Sun for a continuous period of about 36 days
  - During these periods, in November-January and May-July, the FDF predictive accuracy is considerably degraded.

# Nominal Mission Definitive Accuracy



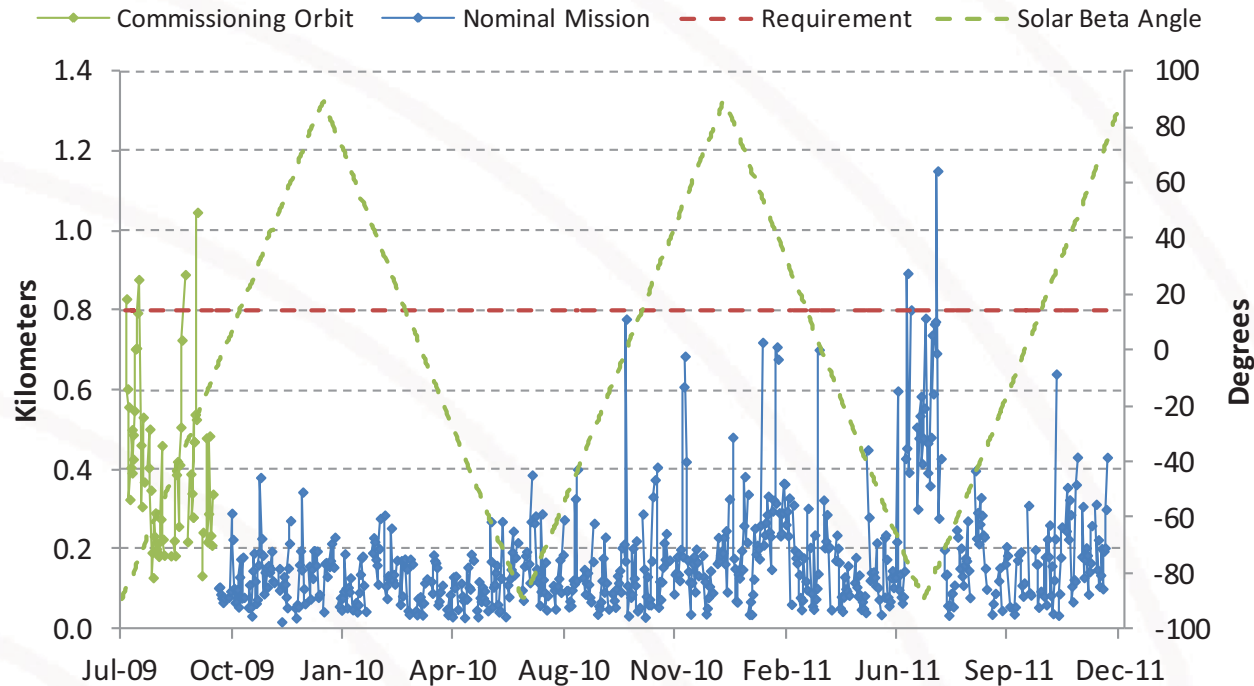
- Radial position RMS definitive accuracy (left) only violated requirements once in the nominal mission.
- Radial accuracy exhibits a periodic effect due to Earth-LRO orbit observation geometry.

- Total position RMS definitive accuracy (right) did not violate requirements in the nominal mission.
- Total position accuracy is worse in the commissioning orbit and during full-Sun periods, due to weakness of LP150Q in this regime.





# Nominal Mission Predicted Accuracy



- 84-hour prediction accuracy violated requirements three times during the nominal mission, all during a full-Sun period.
- The LRO Beta angle is shown, illustrating the correlation between predictive accuracy and full-Sun orbit illumination (Beta near  $\pm 90$  degrees).
- This correlation is not as strong here in the nominal mission orbit as it is in the later extended mission orbit.

# Issues in the Extended Mission

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- The LRO nominal mission ended on December 11, 2011 and LRO returned to the 40x180 km altitude frozen orbit.
- In the elliptical orbit, the FDF began to experience a greater frequency of requirement violations. In particular...
  - Radial and total definitive accuracy were worse than in the nominal mission,
  - Predictive accuracy during full-Sun periods was worse.
- An effort was launched to study potential improvements to LRO OD in this regime.

# OD Improvements in the Extended Mission



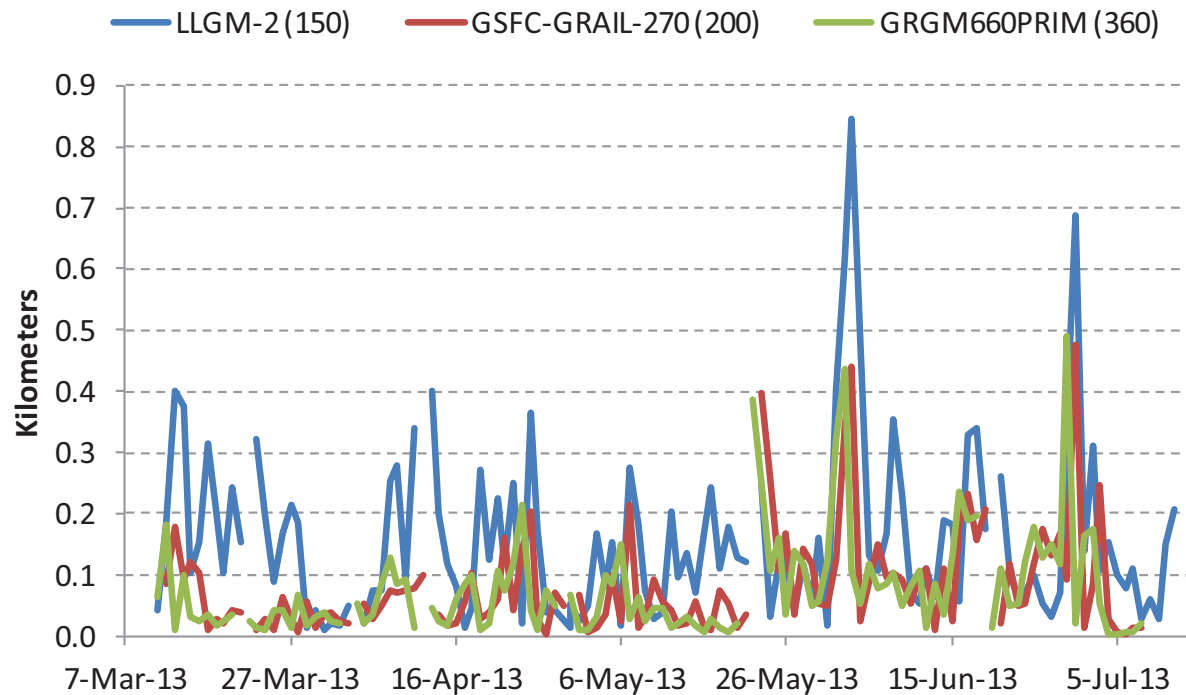
- Improved lunar gravity models
  - In summer 2012, new gravity models derived from LRO and GRAIL data were available.
- Orbit prediction during full-Sun periods
  - GTDS has a multi-plate area model for lunar orbiters.
  - This model can compute some appendage attitudes analytically or via external input for the spacecraft, solar array, and high-gain antenna.
- Refining the OD estimation arc length
  - Assess changing the OD arc from a 60-hour arc to 36 hours.
- Implementing a constrained plane for estimation
  - Ameliorating the cross-track error in edge-on geometry by constraining the OD to a higher-accuracy a priori plane.

# Improved Lunar Gravity Models

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- The LLGM-2 and GSFC-GRAIL-270 models were evaluated
  - I don't think these models have been publicly released, but improved descendants are available.
  - LLGM-2 incorporates LRO tracking,
  - GSFC-GRAIL-270 is a GRAIL model.
- Both models improve accuracy over LP150Q in the extended mission orbit.
- Ultimately, GSFC-GRAIL-270 was proven to be a more robust choice for the extended mission orbit.

# Gravity Model Analysis Results



- The plot shows definitive position RMS total position error. The numbers in parenthesis in the legend show the order of the field used.
- One of the latest GRAIL models, GRGM660PRIM, is included for comparison.
- I don't have an LP150Q series for this time span because the LLGM-2 model was in use operationally in the FDF over this time span.
- GSFC-GRAIL-270 and GRGM660PRIM are quite similar and both are improvements over LLGM-2.

# Orbit Prediction During Full-Sun

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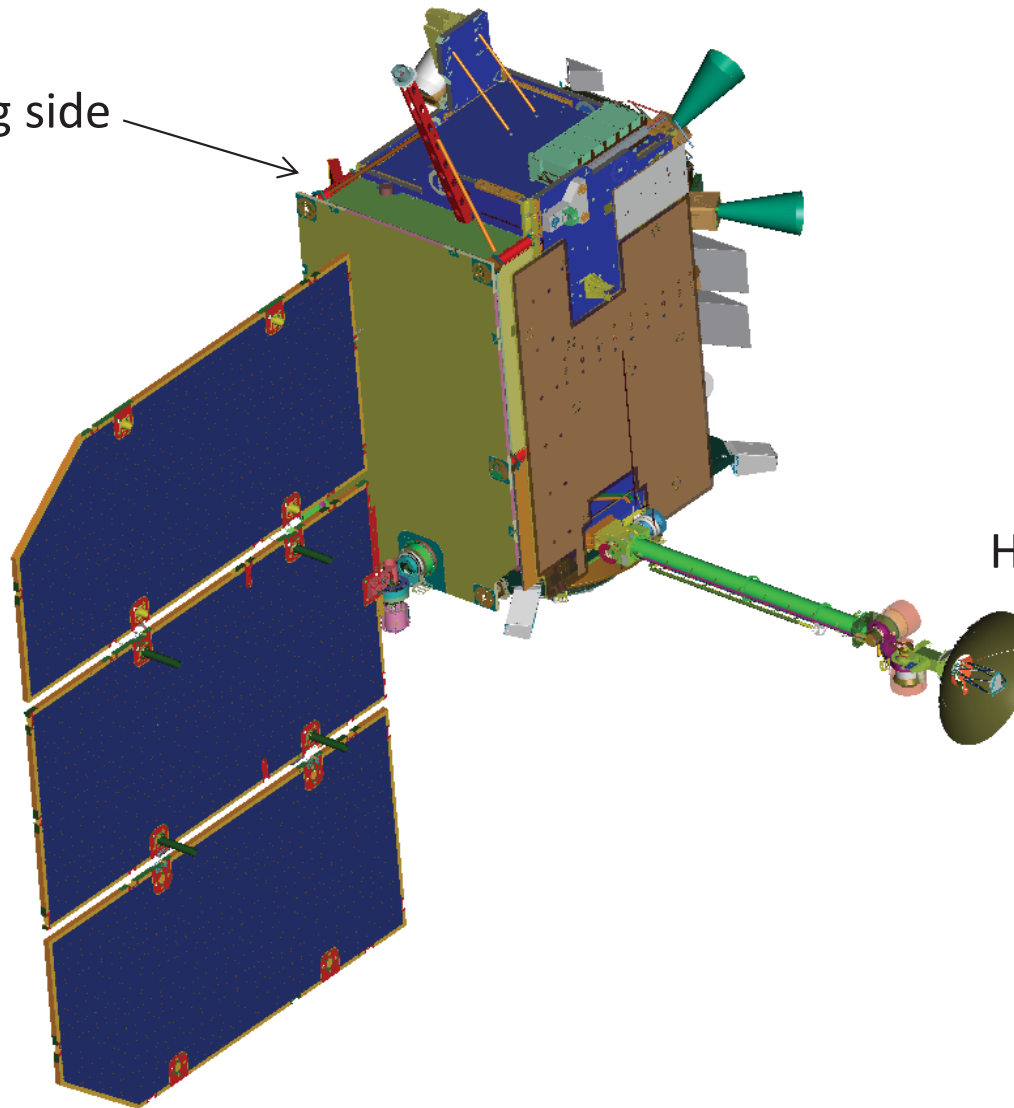
- In the extended mission, 84-hour prediction accuracy frequently exceeds requirements near Beta  $\pm 90$ , when LRO is in a full-Sun exposure orbit for about a month, typically in November-January and May-July.
- Operational OD uses only a simple “cannonball” area model.
- GTDS has a multi-plate area model for lunar orbiters, with the option of analytic computation of spacecraft and solar array pointing, or input of external pointing files.
- Use of the analytic model multi-plate area model yielded little improvement in predictive accuracy.
- Use of the multi-plate area model with definitive attitude data eliminates all requirement violations.
  - Definitive attitude data is not available in time for daily operations.
  - Further investigation of methods of improving predictive accuracy are ongoing.



# LRO Spacecraft Configuration

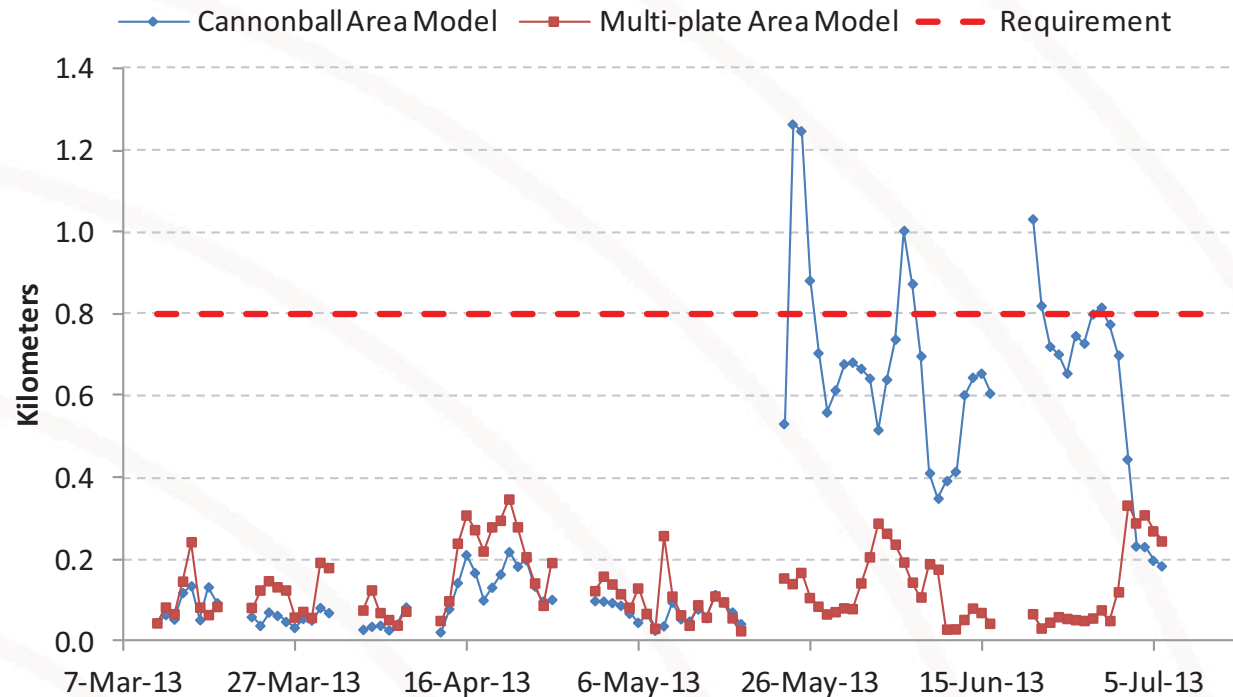


Moon-facing side



High Gain Antenna

# Full-Sun Analysis Results



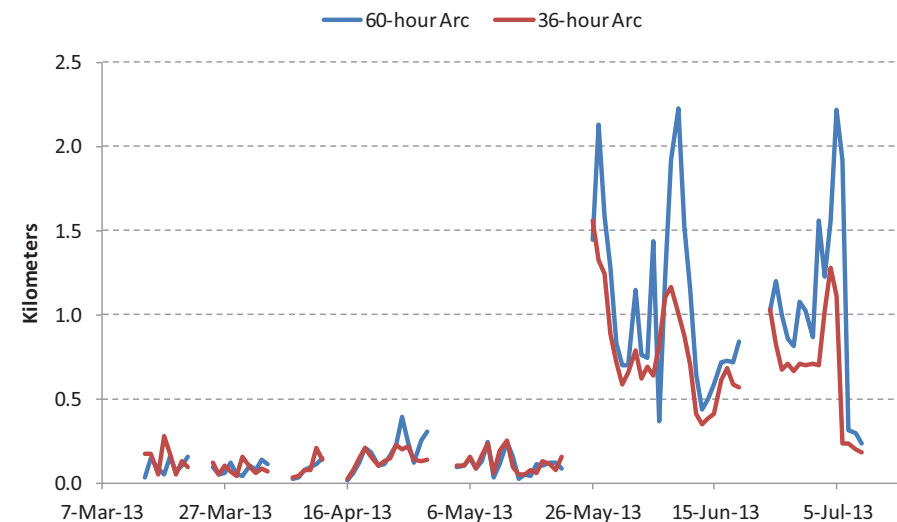
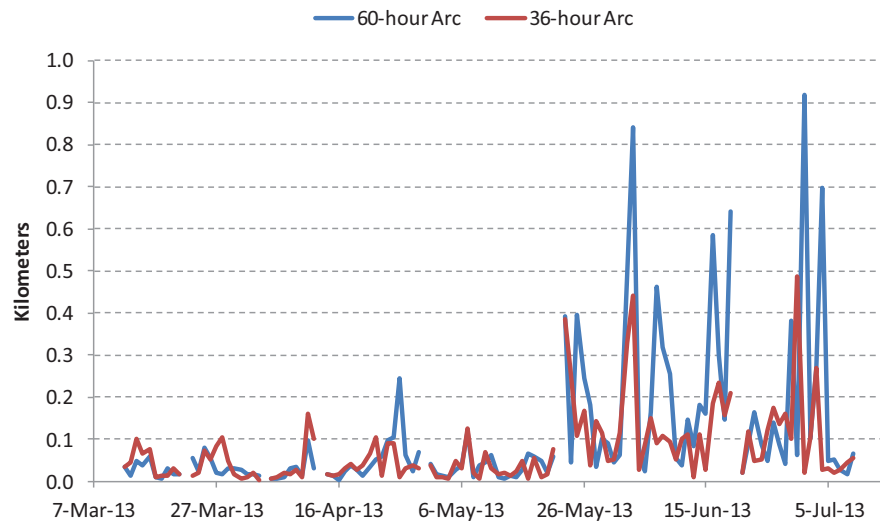
- LRO was in full-Sun from May 22 to June 29.
- The multi-plate area model, in this case using definitive attitude input, eliminates all the requirement violations during full-Sun.
- The multi-plate model is poorer in the normal eclipsing orbit, perhaps because the series applied a value of CR that was estimated using the cannonball model, and the value may not be optimal for the multi-plate model.

# OD Arc Length and Constrained Plane



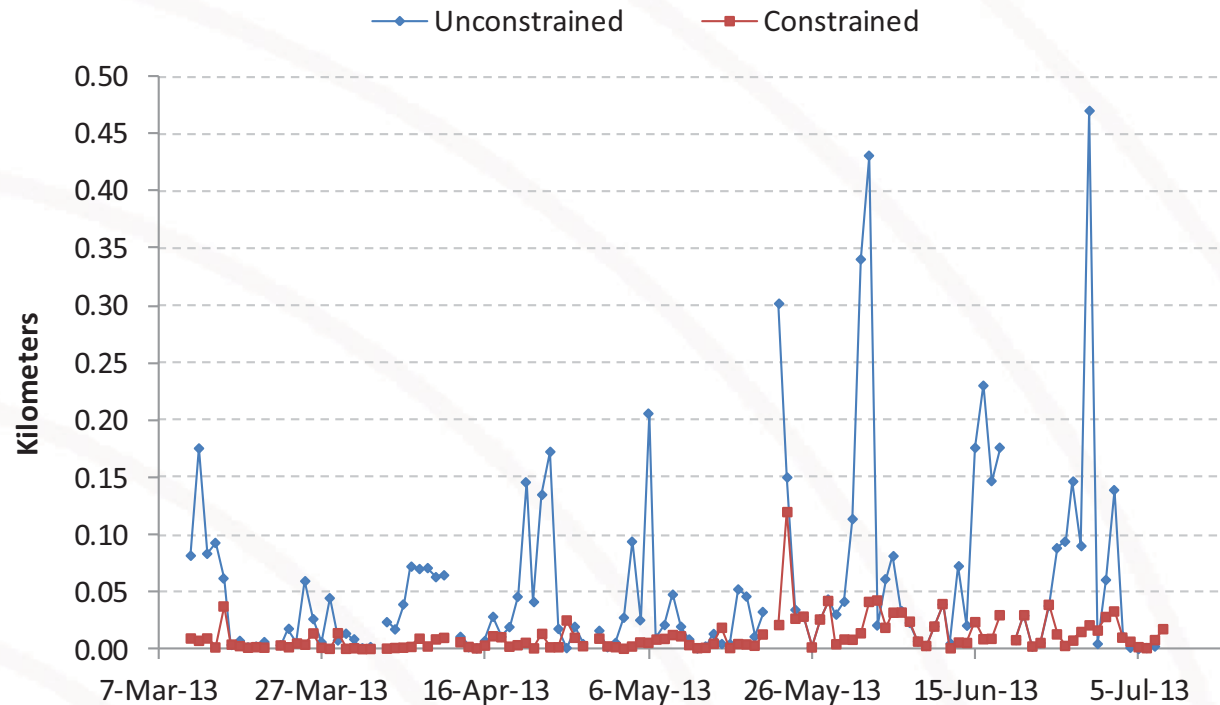
- Refining the OD estimation arc length
  - The FDF used a 60-hour tracking data arc for LRO OD, based mainly on the history of support for the Lunar Prospector mission.
  - A 36-hour tracking data arc was shown to provide improvements in definitive and predictive accuracy.
- Implementing a constrained plane for estimation
  - Cross-track track OD error is significant when the LRO orbit is turned edge-on to the Earth. Cross-track accuracy is good when the LRO orbit is viewed face-on.
  - Initiating constraints to the a priori INC and RAAN when the LRO orbit is within 45 degrees of the Earth-Moon line was found to improve definitive cross-track accuracy.

# OD Estimation Arc Length Results



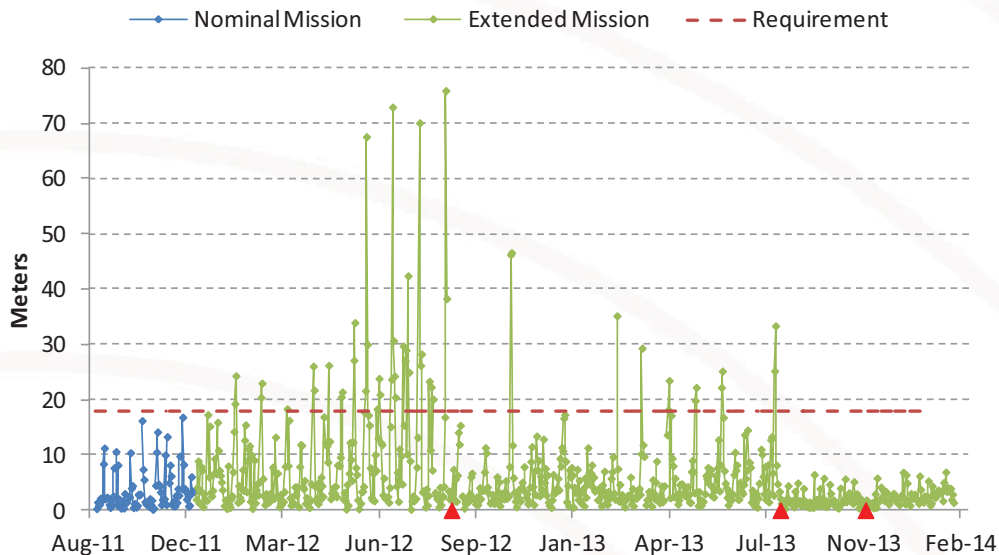
- RMS total definitive accuracy (left) and 84-hour predictive accuracy (right) are both better with a 36-hour estimation arc than with a 60-hour arc, using the GSFC-GRAIL-270 (200) gravity model.

# Constrained Plane Analysis Results

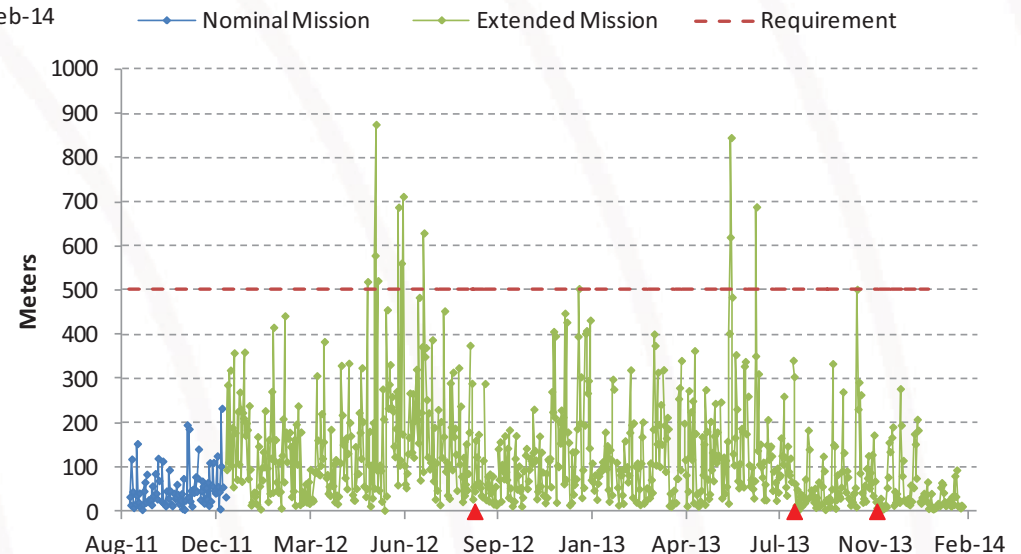


- This plot illustrates position RMS cross-track definitive accuracy.
- The unconstrained series illustrates the periodic (every two weeks) degradation in accuracy due to edge-on view of the LRO orbit plane.
- Cross-track definitive accuracy is good in the “troughs” when the plane is viewed face-on.
- The constrained series largely eliminates the periodic effect by constraining the plane during edge-on view to the plane estimated in a trough (face-on view).

# Extended Mission Definitive Accuracy



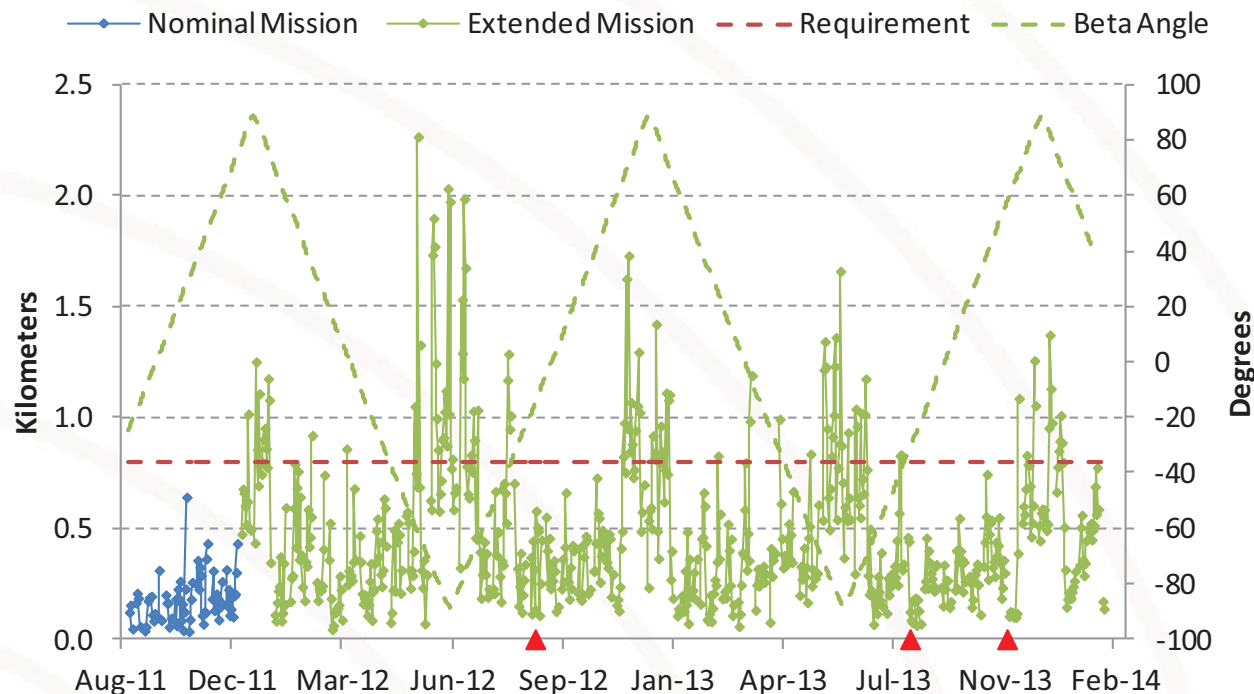
- Radial position definitive accuracy (left) failed frequently in the extended mission orbit using LP150Q.
- Newer gravity models greatly improve radial definitive accuracy.
- The red triangles denote...
  - Implementation of the LLGM-2 and a 36-hour OD arc,
  - Implementation of GSFC-GRAIL-270,
  - Implementation of constrained plane.



- Total position definitive accuracy (right) failed frequently in the extended mission orbit using LP150Q.
- Newer gravity models improve total definitive position accuracy.
- The constrained plane was implemented in November 2013, only two months of data since then are shown.



# Extended Mission Predicted Accuracy



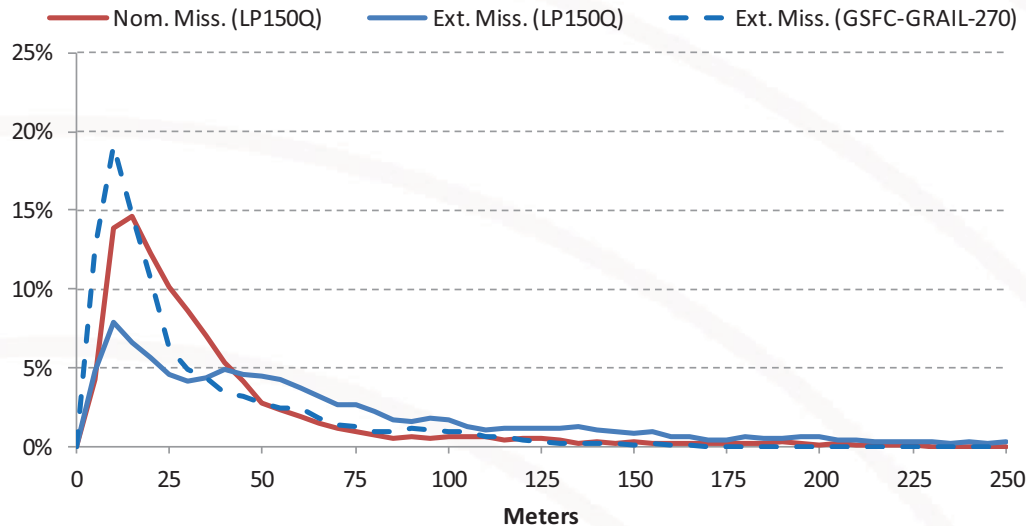
- 84-hour prediction accuracy failed requirements frequently during the extended mission, always during full-Sun periods.
- The LRO Beta angle is shown, illustrating the correlation between predictive accuracy and full-Sun orbit illumination (Beta near  $\pm 90$  degrees).
- This correlation between predicted accuracy and full-Sun illumination is much stronger in the extended mission orbit than in the nominal mission orbit.
- New gravity models improve predicted accuracy but do not eliminate the violations, which are primarily due to coarse spacecraft modeling for solar radiation pressure.

# Comparison to High-Precision OD

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- The LOLA team produces high-accuracy ephemeris files using GEODYN
  - These orbit solutions use the same S-Band tracking data that the FDF OD uses, but employ high-accuracy force modeling and media corrections.
  - The latest LOLA-produced solutions are accurate to about 10 meters in total position.
- Comparison of the FDF OD to these ephemeris files enables assessment of the true accuracy of the FDF solutions and evaluation of the definitive overlap technique as a proxy for definitive accuracy.

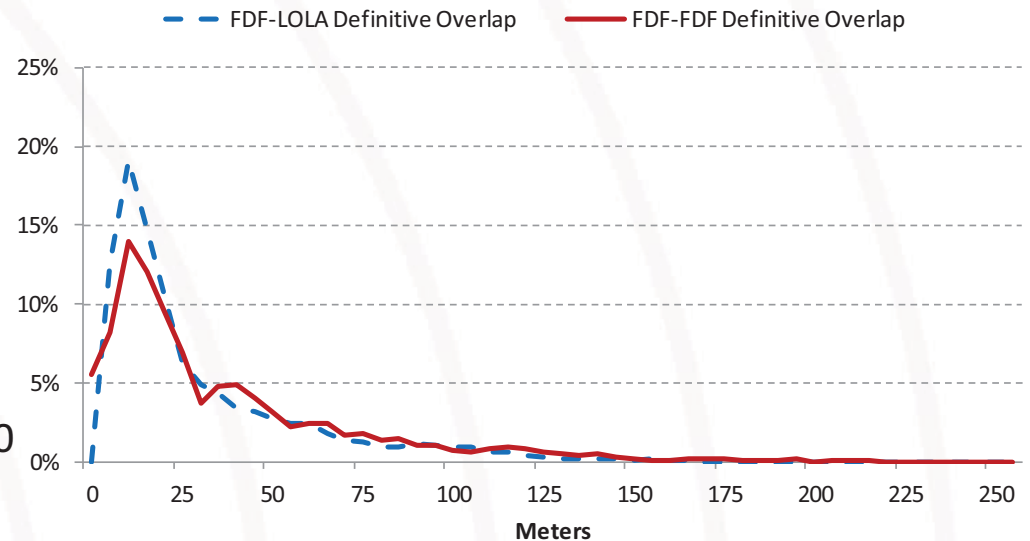
# Comparison of FDF and LOLA Solutions



• The distribution of total position difference between FDF definitive orbits and LOLA definitive orbits (left) shows a 2-sigma error of...

- 115 meters in the nominal mission with LP150Q,
- 225 meters in the extended mission with LP150Q,
- 100 meters in the extended mission with GSFC-GRAIL-270.

- A comparison of the distribution of FDF-FDF definitive overlaps with the FDF-LOLA definitive overlaps (right) using GSFC-GRAIL-270 in the extended mission orbit shows...
  - The FDF-FDF definitive overlaps are consistent with the FDF-LOLA definitive overlaps.
  - The 95th percentile of FDF-LOLA compares is 115 meters,
  - The 95th percentile of FDF-FDF compares is 100 meters.



# Conclusion

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- LRO definitive and predictive accuracy requirements were easily met in the nominal mission orbit, using the LP150Q lunar gravity model.
- Accuracy of the LP150Q model is poorer in the extended mission elliptical orbit.
- Later lunar gravity models, in particular GSFC-GRAIL-270, improve OD accuracy in the extended mission.
- Implementation of a constrained plane when the orbit is within 45 degrees of the Earth-Moon line improves cross-track accuracy.
- Prediction accuracy is still challenged during full-Sun periods due to coarse spacecraft area modeling
  - Implementation of a multi-plate area model with definitive attitude input can eliminate prediction violations.
  - The FDF is evaluating using analytic and predicted attitude modeling to improve full-Sun prediction accuracy.
- Comparison of FDF ephemeris file to high-precision ephemeris files provides gross confirmation that overlap compares properly assess orbit accuracy.